Offshore Wind Farms – the Need for Metocean Data

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Introduction

The wind power community has a long record for onshore design and construction of wind turbine foundations, whereas the offshore wind power is still in an embryonic phase but with aggressive and ambitious plans for developments. Despite the many and obvious differences between traditional oil and gas structures and wind turbine foundations, there are much more similarities than differences in the requirement to high quality metocean data. This paper outlines the methodologies for establishing the metocean data basis including examples from offshore wind farms. The aim is to present an overview rather than all the details, which are better found in text books and dedicated technical papers.

Metocean data and parameters – definition

Meteorological data (wind, atmospheric pressure, air temperature, etc.) and **ocean**ographic data (waves, current, water level, salinity, water temperature, ice, etc.) are often not only lumped together in the term metocean data, but are also typically lumped together in one design basis for environmental parameters. Furthermore, the two sets of parameters are deeply related as the meteorological conditions are the driving forces for waves, surge levels and currents. Measurement programs will typically record both types of data. The term *hydrographic* data is often used for the oceanographic data. This paper only addresses the oceanographic/hydrographic data, but not the meteorological data.

A particular oceanographic quantity is ice. In certain waters ice can be a dominant parameter for design loads as well as for maintenance planning. Information on ice data is typically based on historical data only, and it is treated differently than the other metocean parameters. Ice is therefore not considered further in this paper.

Traditional offshore structures vs. wind turbine foundations

Any structure used in offshore oil and gas exploration and production constitutes a vital part of a successful energy production, vital both in terms of construction costs, of safety, of human lives and the environment, and in terms of revenues from the production. It has therefore been both a necessary and an accepted effort to produce high quality data for the metocean climate at each operation site.

An offshore wind turbine foundation is typically simpler and much cheaper to build than an oil platform. Furthermore, the wind turbine will be un-manned except for maintenance and repair, the environmental impact from a damaged structure is limited, and the value of the energy production per foundation unit is far less than the value from oil production from a platform. So if only one or very few foundation units were considered, it could be tempting to use less accurate, less reliable, and hence less costly metocean data than what is accepted within the oil and gas industry. However, most offshore wind farms will include a large number of foundations, which means that the total costs for the foundation units are significantly influenced by the metocean design parameters.

For most of the structures used within the oil and gas production industry the design loads are governed by the **ocean**ographic (or hydrographic) parameters: waves and currents. For the existing offshore wind turbines the most important load comes from the **met**eorological forcing: the wind. However, the wave and current loads are not negligible for the design loads even in the shallower water depths. Furthermore, the hydrographic conditions determine the installation windows, conditions for boat access during maintenance and seabed stability including scour protection, which also constitute important parts of the total economics of a wind farm. With more recent wind farm developments looking at deeper water prospects, the hydrographic design basis will attain increasing importance.

Application areas for metocean data

The following main areas require information on (wind), waves, water level and current:

Installation planning: daily/monthly statistics for waves, water level and currents for estimating downtime and associated costs

Maintenance planning: daily/monthly statistics for waves, water level and currents for estimating downtime and associated costs

Fatigue of foundation unit: annual statistics of waves

Design loads on foundation units: extreme values of waves, water level and currents, preferably including joint statistics (also with wind)

Design of scour protection: extreme values of waves, water level and currents, preferably including joint statistics.

In deeper waters, where floating foundation units will be considered, there will be additional need for dynamic load and response calculations. For some existing foundation units such dynamic analysis is required due to structural natural frequencies being close to values where the waves have considerable energy. Such analyses will require more detailed hydrographic input data, and analysis philosophies similar to what is used for floating production systems in the oil and gas industry may be introduced.

As will be discussed later, hydrographic data from forecast models can be used to further optimize installation and maintenance planning.

Main Sources of metocean data

The main sources from where to obtain metocean data vary from the very initial stages of a project to the detailed design stage as the requirement to accuracy and reliability increases. In the initial stages "global" data from the area or nearby areas may serve as a first set of information. However, caution in use of such data is warranted, in particular if the data source refers to deeper waters than the wind farm site. "Global" data can be found e.g. in summary statistics based on reported and analyzed ship observations, from satellite measurements or from public measurement campaigns. Data for preliminary assessments are not discussed further in this paper where the focus in on site specific data for use in planning and design.

For the detailed planning and design stages of an offshore wind farm it is necessary to develop accurate and reliable data as basis for statistical analyses. The optimal set of data consists of long term measurements at the site. However, such data sets are very rare, since measurement campaigns are not launched until a site has been selected, which leaves only maybe a few years or even less time of data collection. The most commonly used substitute - or preferably supplement – to measurements are hindcast data. Hindcast data refer to numerical modelling of waves, water levels and currents using wind and atmospheric pressure plus tidal forcing as boundary conditions.

The establishment of the two types of data, measurements and hindcast, will be reviewed next followed by examples from offshore wind farms and sections on data post-processing to produce the required basis for availability statistics and design loads.

Measurement of waves, current and water level

Various public documents can assist in defining the requirements to measurement campaigns in terms of recording intervals, accuracy, resolution and data analysis. Refs /1/ to /6/ provide such information. Table 1 below summarizes suggested minimum values for recording intervals, averaging period and sampling frequency for the oceanographic data.

Table 1 Suggested minimum requirements to recording interval, averaging period and sampling frequency

Parameter	Recording Interval	Averaging Period	Sampling Frequency
Waves	1 hour	20 min	2.5 Hz
Currents	10 min	10 min	1 Hz
Water Levels	10 min	1 min	1 Hz

It is emphasized that with today's technology it is recommended to use continuous recordings with 2-5 Hz sampling frequency as far as possible. This allows for more accurate post processing of data into well defined standard parameters.

The longer the duration of a measurement campaign the better since a longer data coverage leads to less uncertainty arising from extrapolation to the design return period. The measurements need to capture the essence of the stochastic variation in all the important parameters, if measurements alone shall form the basis for the metocean design basis. The duration shall thus be of the same order of magnitude as the return period of the design values. If return period of design values is 50 years then at least 10 years of data should be obtained. More often the measurements are combined with hindcast and shorter durations of the measurement campaign can thus be applied.

Types of sensors
A number of different technologies are available for measuring oceanographic data. Some sensors applied to measure different parameters are summarized below. The summary is not meant to be exhaustive but includes the most commonly applied sensors.

Water level: pressure gauge, step gauge, radar
Currents: Acoustic Doppler Current Profiler or ADCP (current profile over entire water depth), electromagnetic, acoustic or standard point current meters
Waves: Radar, Laser, ADCP with wave option, wave buoy, wave staff. Some of these instruments can provide directional information.

Some sensors can be fitted so that both water level, current and waves are measured.

Most of the sensors have built-in or associated software that produces the derived parameters such as significant wave heights, mean period, and mean velocity. Some sensors require additional software to produce the required parameters, but such software is available from a number of vendors and within the survey companies performing measurements.

Hindcast Methodology
Hindcast refers to the use of historical meteorological data (atmospheric pressure and wind) to drive numerical models for water level, currents and waves, hence producing estimates on oceanographic conditions in the past. It is noted that the use of hindcast data (as well as measurements) implies an assumption of the past being representative for future conditions in a statistical sense. Effects of possible changes in climate should be considered in the final analysis

Currents and water levels are generated by a hydrodynamic (HD) model, and waves are hindcast using a wind-wave model. For both types of models the entire water area affecting the location in question should ideally be included in the model. In addition to the pressure and wind fields, the models need information on water depth (bathymetry), and the hydrodynamic model will also need tidal level information in open sea areas.

There is a number of HD and wind-wave (or just “wave”) models available on the market. The examples shown in this paper are all from DHI’s MIKE 21/MIKE 3 suite of programs, which are used at DHI and are commercially available as well.

Hydrodynamic modelling
Hydrodynamic models fall in two main categories: one provides the depth averaged current (2D), the other provides the depth varying current (3D). The latter type of model requires more input data, e.g. on temperature, salinity, density variation over water depth, and is computationally more demanding. Which of the two types of model to apply depend on the physical conditions in the water body being investigated and on the requirement to the output. For wind farms typically being erected in shallower waters a 2D hydrodynamic model will often be adequate.

A calculation mesh in DHI’s MIKE 21 HD model can either be made up of unstructured triangular elements with varying sizes or structured rectangular calculation elements. The size of the mesh/grid shall take due account of the variation in bathymetry and any local variation that can affect the conditions at the location in question.

The mean water depth is given at each of the cells in the computational grid. The waters depth information is either from sea maps (electronic versions) or from dedicated bathymetric surveys. The atmospheric pressure and the wind speed and direction shall also be given for each cell. These values are normally interpolated from a more coarse grid than the HD model. At the boundary of the model tidal elevation has to be specified. Tidal information has traditionally been available from coastal tide stations, but is now also available in open waters from satellite data, which provides for a much more flexible and often more convenient selection of boundary location. The numerical simulation is dynamic, i.e. the driving forces (wind, pressure, model boundary conditions) vary in time and space, and are typically updated each 15 minutes for a HD model. The model then calculates the surface elevation variation and the current fields as function of time in each grid point.

Fig. 1 shows an example of a snapshot of elevations and currents from a simulation of the severe storm over the North Sea in December 1999 with a 2D model using a rectangular grid. The colour scale indicates the surface elevation and the arrows the current speed and direction. At the particular time shown in the figure, the water level is high close to the German coast and at the English Channel, whereas the level is low at the English coast. This is due to the wind forcing the water to the western part of the North Sea.

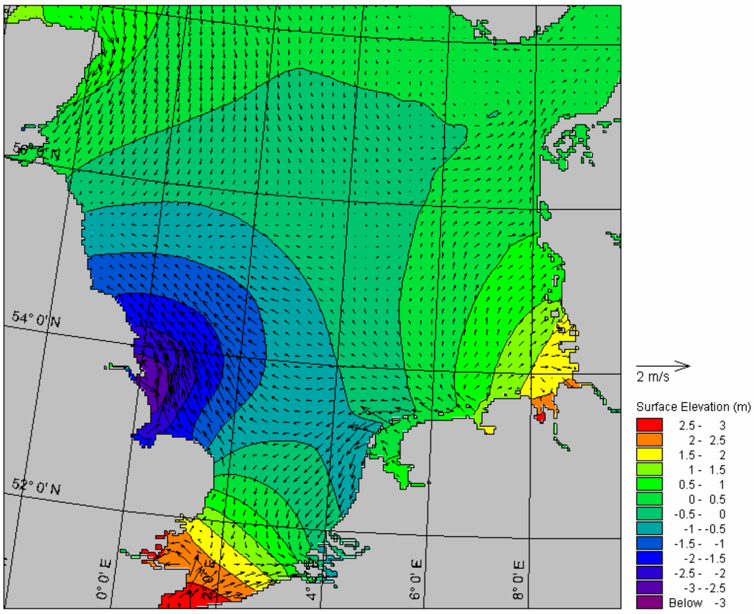

Figure 1 *Snapshot of 2D hydrodynamic model output: Elevations (colour) and currents (arrows) on 3 December 1999, 15 UTC*

Fig. 2 shows the output from the 2D model in one grid point as function of time. At this particular grid point the maximum water level is reached around six o'clock in the evening of December 3. The level variation clearly shows both the tidal influence with two peaks a day and the storm surge during December 3 and 4.

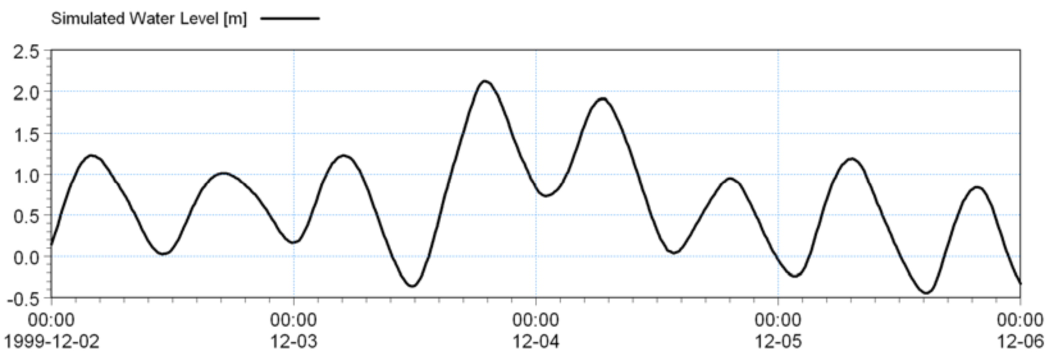

Figure 2 *Output from 2D hydrodynamic model in one grid point as function of time*

Detailed information on HD models can be found in Ref /7/.

Wave modelling

Wave modelling cover in reality models of different classes, from parameterized and full spectral wave models to so-called short wave models, where time series of water surface elevation for individual waves is simulated. In this paper only the full spectral model type is addressed since this type of model is the main type for deriving metocean design data.

A computational mesh from a spectral wave simulation with DHI's MIKE 21 SW model focussing on Borkum Riffgrund in the German Bight is shown in Fig 3. A "flexible mesh" like the one in Fig 3 may also have been used for the hydrodynamic model.

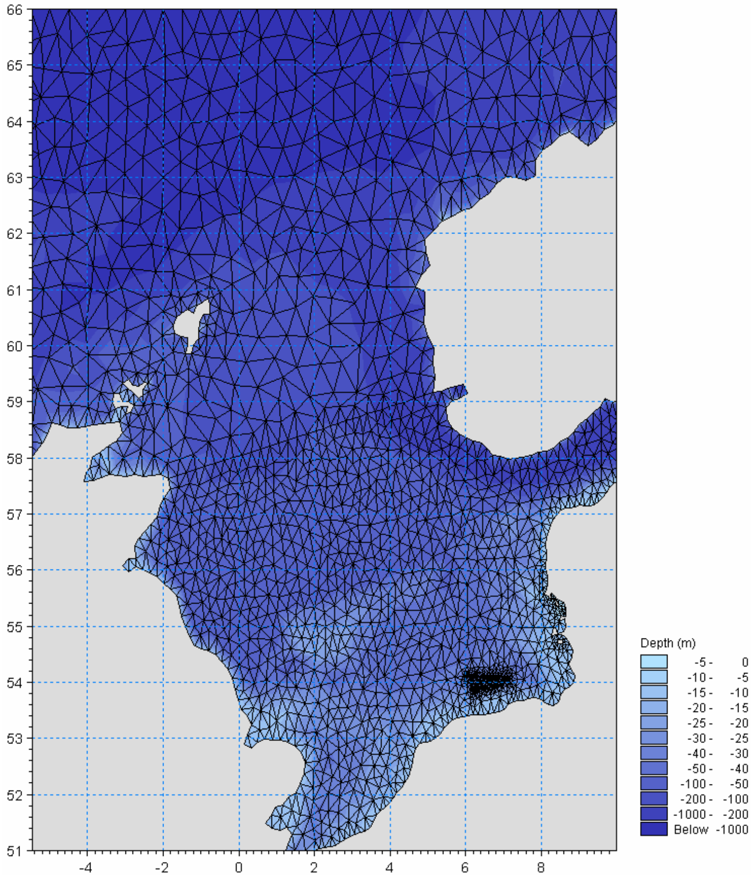

Figure 3 *Computational mesh for spectral wave model with focus on wind farm in German Bight (Borkum Riffgrund)*

The input data at each cell is the water depth and the wind speed and direction as function of time. In shallow water areas where substantial variation in mean water level (due either to tidal or wind forcing) occurs, the model input can be expanded to include the level variation as well as currents from a HD model. Similar to the HD models, the numerical wave modelling is dynamic, and the input fields are typically updated at all grid points each 15 minutes. The output from the model is the wave energy distributed on frequency and direction. From this information the key sea-state parameters are derived, including significant wave height H_{m0}, peak period T_p, mean period T_{01} (or T_{02}) and mean (peak) wave direction. It is noted that great care shall be exercised in deriving these bulk parameters since a sea-state may well include not only the wind waves but also longer period swell waves that are important in particular for the installation processes. An example of spectral output (here shown in a polar plot) is given in Fig. 4. The plot shows the energy content as function of wave direction (coming from) and wave period. It is clearly seen that the total sea in this example is made up of two separated contributions from different directions, one from NNW (with periods of 4-5 s) and one from WSW (with periods of 6-8 s).

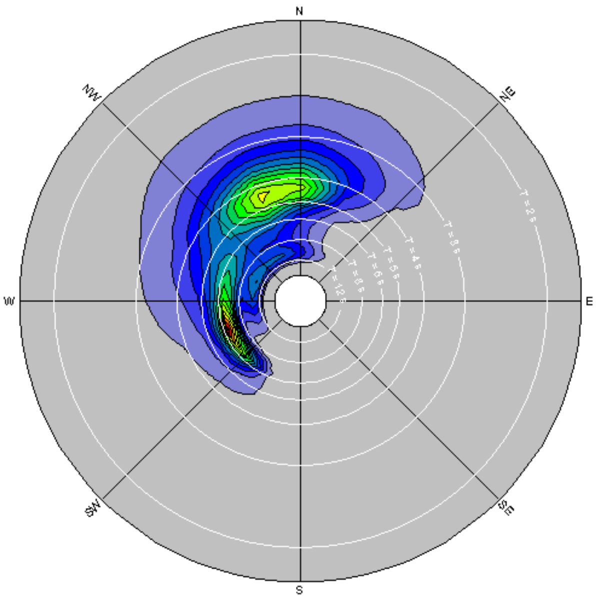

Figure 4 *Example of output wave energy spectra showing two separate sea-state systems*

Fig. 5 shows a snapshot of wave model output, where the colour scale indicates the magnitude of the significant wave height and the arrows indicate the wave direction. Fig. 6 shows the output at one grid point as function of time.

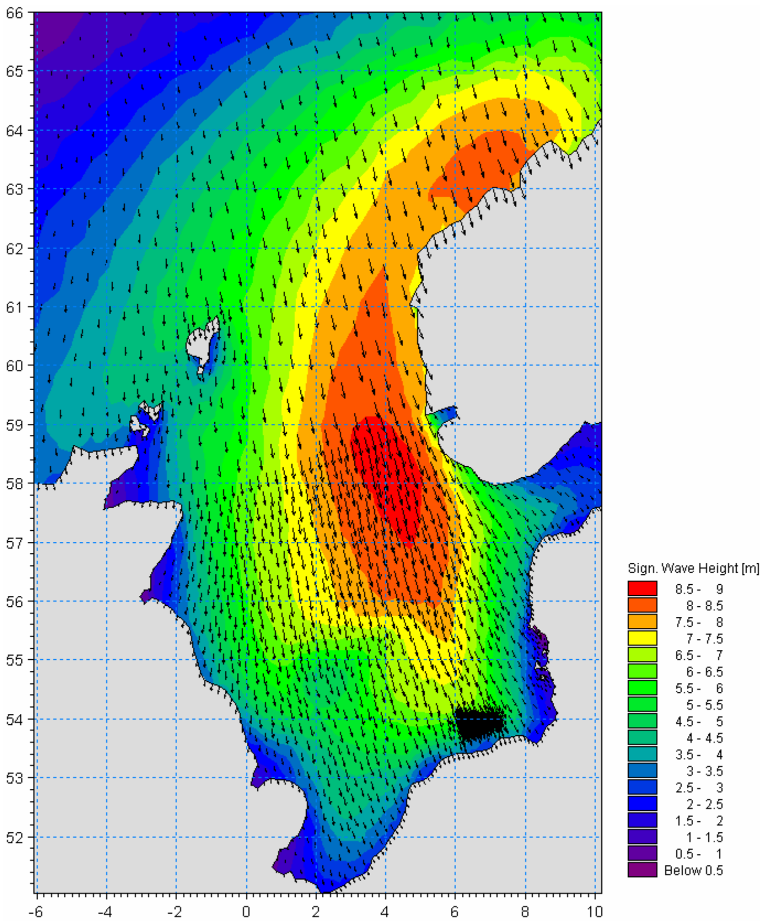

Figure 5 *Snapshot of wave model output: Significant wave height (colour) and wave direction (arrows) on 15 December 2003, 12 UTC.*

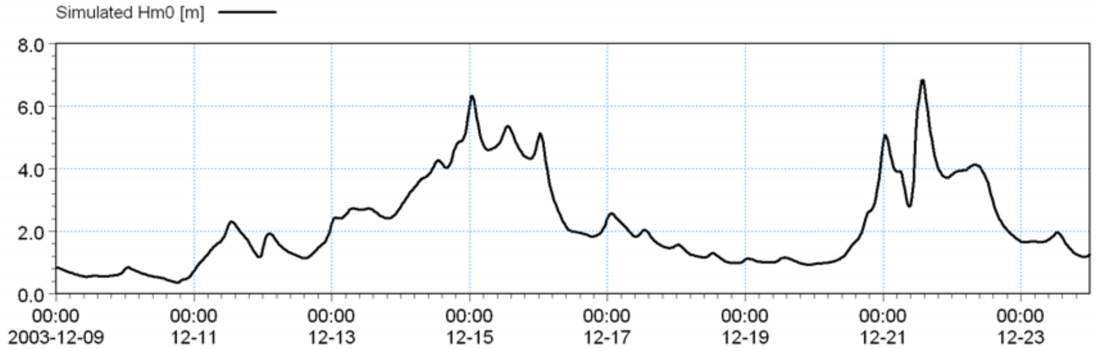

Figure 6 *Output from wave model in one grid point as function of time*

For a given site, the output from only a few number of grid points are normally adequate for further analysis, either for water level (which varies moderately within the distances of offshore wind farm areas), currents or waves.

Detailed information on numerical wave modelling can be found in Refs /8/ and /9/.

Typical tasks in a hindcast study
The following tasks are involved in a hindcast study:

- establishing the bathymetric data
- establishing the pressure and wind fields
- establishing tidal information at model boundaries
- setting up HD and wave models, including mesh generation
- calibration of models against measurements
- validation of model (applying revised model parameters) against a second set of measurements
- production simulations using final model parameters and all meteorological input fields (covering for example 10 or 20 years and 50-100 storms)
- quality check of output
- post-processing of data including statistical analyses

The model calibration parameters include e.g. wind friction factors, seabed roughness (or bed friction), and wave breaking parameters. In many cases these parameters will be similar if not identical to the default values, but in other cases different values have to be selected to provide good comparison between the model output and measurements.

With the ever increasing capacity of computers and decreasing cost per CPU it has become both feasible and state-of-practice to hindcast many years of continuous conditions. Storm data can be either extracted from these data for extreme value analysis or storms can be handled separately. The reasons for handling storms separately are that it is feasible with a more detailed meteorological analysis of selected storm events and it is also possible to extend the coverage period. Storms may be selected from a 40 year period whereas a continuous hindcast may cover 10 to 20 years.

Whereas major improvements in both quality of models, in ease of inputting bathymetric data and tidal information, and especially in the user-friendliness of the set-up and execution, these improvements cannot and shall not be seen as substitutes for the cleverness and skills of the metocean specialist. The models are tools for assisting in producing the vital information on metocean conditions

The use of measurements and models for offshore wind farms - examples
Measurements are vital to most offshore wind farm developments as they provide site specific information. However, measurements are rarely initiated in time for them to be the only basis for statistical analysis. Hindcast thus supplements the measurements and hindcast models make extensive use of the measurement for calibration purposes.

Examples of the use of measurements and hindcast models are given in the following sections. It is emphasized that whereas measurements in general provide accurate estimates on “reality”, sensors or measurement technology do have shortcomings or assumptions associated that makes the measurements estimates rather than direct representations of reality. A comparison between measurements and hindcast model data that does not produce a 1:1 relation is thus not necessarily an indication of model errors of insufficiencies. It is prudent to always investigate and consider the quality and accuracy of both the measurements and the model data prior to making final conclusions.

The two locations reviewed below are examples on the use of measurements combined with numerical modelling. There already exists a number of projects where the two types of data sources have been used in similar manners. The exact combination of measurements and numerical models will vary from project to project.

Horns Rev

One of the first sites for a large offshore wind farm in Danish waters as well as world wide was the Horns Rev in the North Sea. Here it was decided to install both a tower for wind sensors and wave measurement sensors. Both ADCP and wave buoys were installed. Data were partly stored on board and partly transmitted to shore for on-line viewing and storage.

In addition to early calibration of the numerical models, the measurements were also used for on-line calibration of numerical models running in forecast mode. Forecast mode means that the meteorological input is from the weather forecast, ie predicted wind fields, and the waves and currents thus becomes water forecast quantities. The forecast was used for the planning of installation of the foundations and turbines.

A validation of the hindcast wave model against measurements is shown in Fig. 6. The wave model has been run with both fixed water level and with varying water level with input from the HD model. For this particular comparison the influence of the varying water level is small. The comparison with measurements is excellent both for the significant wave and for the mean period.

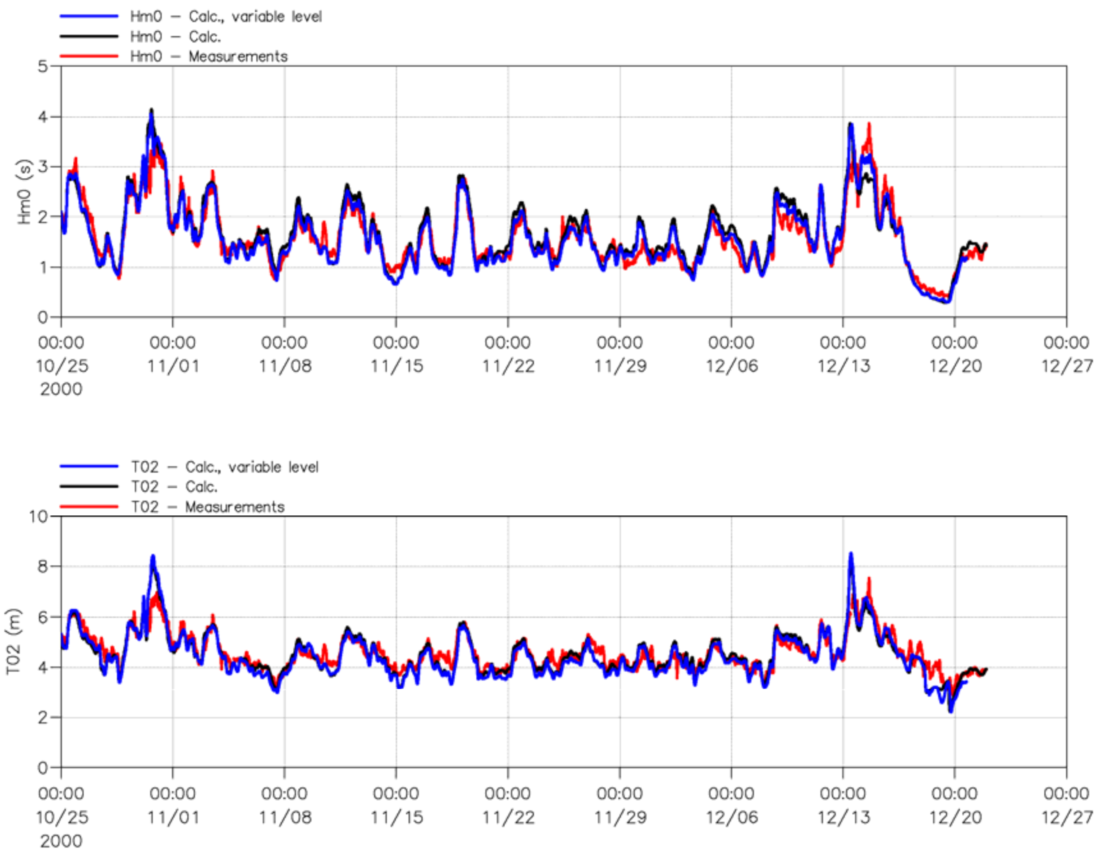

Figure 6 *Comparison between wave model output and measurements at Horns Rev, November-December 2000*

Borkum Riffgrund
Located about 40 km north of the German island Borkum, Borkum Riffgrund is one of the areas being developed for offshore wind farms in the German part of the North Sea. For the metocean design study for Wind Farm Borkum Riffgrund I measurements of wind, waves, water levels and/or currents were available from the locations shown in Fig 7.

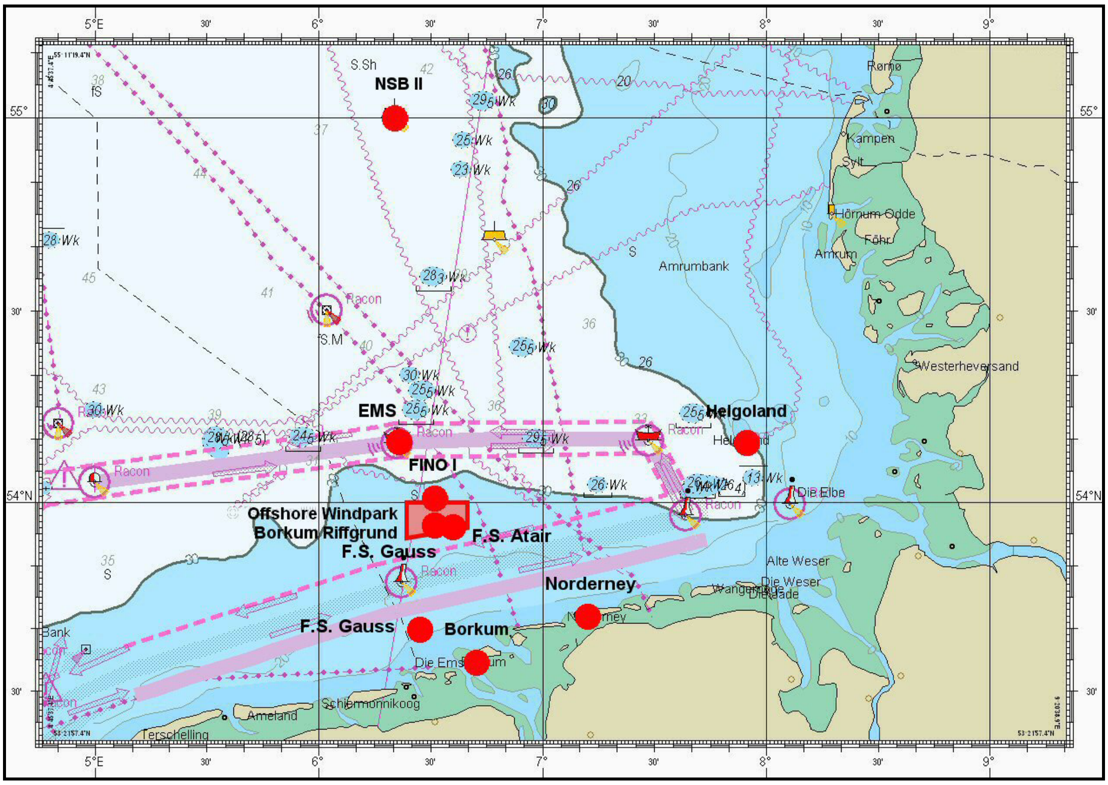

Figure 7 *Location with measurements (wind, waves, water levels and/or currents) for use in metocean design study for Borkum Riffgrund offshore wind farm*

Some data sets covered short periods while other data sets covered several years. While the longer ones were mainly used in the statistical analyses (including correlation analyses), the shorter ones were mostly used for model calibration and validation. A comparison between measured and modelled (simulated) water levels at F.S. Aitair is shown in Fig 8, while Fig 9 shows a comparison of current speeds and current directions at FINO I.

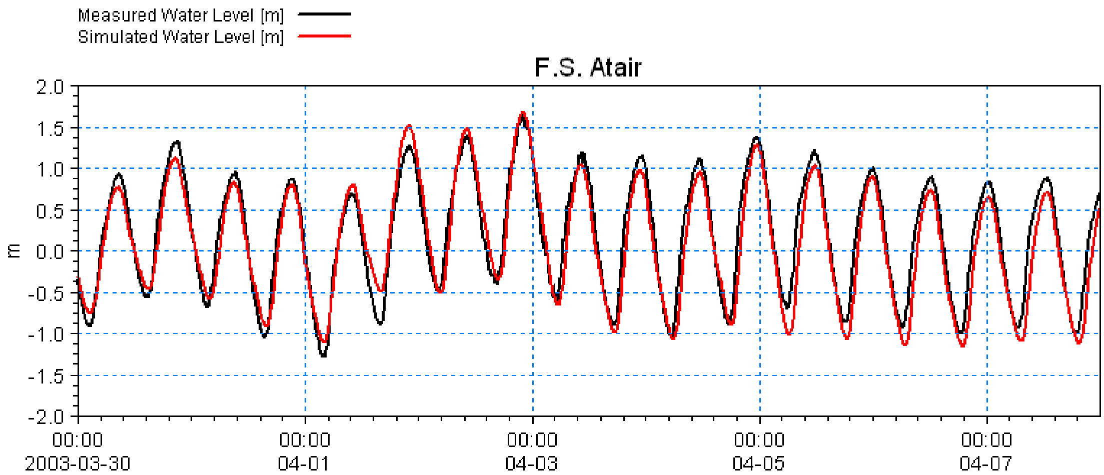

Figure 8 *Comparison between water levels from hydrodynamic model and measurements at F.S. Aitair, March-April 2003*

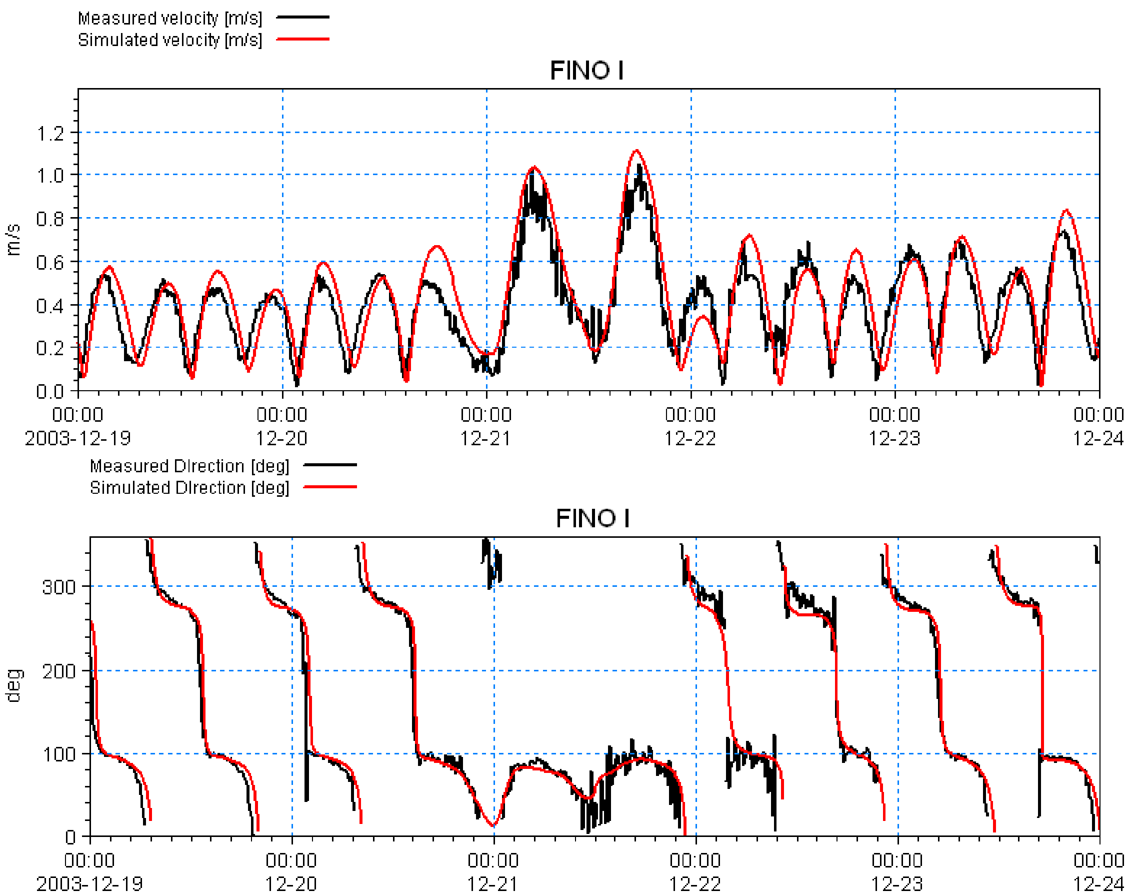

Figure 9 *Comparison between current speeds and directions from hydrodynamic model and measurements at FINO I, December 2003*

By combining measurements and model simulations much more accurate metocean design conditions were obtained, than if only one of the two had been applied.

Design basis – data analyses

Once the data base of metocean data has been established from measurements and hindcast models, the data shall be analysed statistically in various ways to produce information that is useful for design and planning (installation, maintenance). The two applications require different types of parameter values and hence different types of analyses.

Data for design loads often refer to the return period like the 100 year wave height, which is the value that is expected to be exceeded only once in 100 years. Alternatively, it is the value that has an annual exceedance probability of 1%. Depending on safety philosophy other annual probability levels may apply. Design values are in general values that are rarely seen or exceeded. Rarity as implied by the 100-year return period should, however, not be confused with the number of years to pass by before the event happens. The design event might happen the day after the installation has been completed. In fact, there is more than 33% probability that a 100-year design value will be exceeded within a 40 year lifetime of a structure.

Statistics for planning purposes refer to more common conditions, such as those likely to occur during the installation season, which will often be chosen as part of the milder season to minimise risk of downtime.

Design data – Extreme value analysis

The most common data basis for extreme values is storm data, i.e. waves, water level and currents occurring during storms. If all extremes from many years are on record, then an annual max extreme value analysis can be performed. A more common analysis is, however, the peaks over threshold (POT) analysis, in which all peaks above a certain threshold are used, i.e. more than one data from each year can be included in the data. The extremes have to be separated in time by e.g. 24 hours to ensure independency. An extreme value distribution is then fitted to the data and used to extrapolate to the required low probability levels applied in design. A common distribution function being applied for significant wave heights is the Weibul distribution. In general, neither the choice of distribution function nor the data fitting procedures are unambiguous. A careful examination of the fit to the data and assessment of possible outliers in the data form part of the evaluation process towards final determination of design values. Despite the availability of comprehensive software for statistical analyses, there remains a fair amount of common sense, or experience and knowledge, to be invoked in the final selection of the design values.

The statistical methods have mainly been well developed for single parameters, such as water level, significant wave height, or current speed. When a second parameter such as direction is involved, available procedures are much less developed. Consider a case where directional design values are requested for 45 degree sectors, i.e. 8 directional sectors. Each directional sector will thus on average have only one eighth of the data that is available for the omni-directional analysis. This alone introduces a larger uncertainty for each set of directional extremes. The derivation of directional values is thus far from being trivial. Methods aiming at optimising the use of information and taking into account the correlation of data have been introduced, see eg Ref /10/ It is noted that even fully axi-symmetric structures may require directional design values if a probabilistic approach is chosen for design. It shall be noted that the directional definition in most cases use wind and waves coming from but current going to.

It is often assumed that the wave period is related to the wave height through a simple relation. However, more refined statistics are required if the load or response is sensitive to the period. Such methods are being used within the offshore industry, e.g. for floating production systems, and similar methods might be required for very dynamic foundations and certainly for floating foundation units. For water levels and currents the driving forces and hence the output can be partly deterministic (tidal forcing) and partly stochastic (meteorological forcing). This means that special care shall be exercised in addressing the components when performing extreme value statistics.

Combining say 100-year design values for (wind) waves, current and water level to produce the design load will most certainly produce a load larger than the true 100-year load since the assumption of simultaneous and collinear loads is too simple and conservative. Ideally, the loads due to wind, waves and current should be combined and the statistical extreme value analysis performed on the load itself. However, such analysis is rarely if ever performed. Joint probabilities for the occurrence of the extremes are therefore often used as a more appropriate approach and as an avenue to reduce conservatism in the design. For wind turbines an additional complexity appears because a design load may be reached not only for the design wind speed but may appear at the maximum allowable operating wind speed for the wind turbine.

A hydrographic basis will typically include (directional) design values for a number of selected return periods in the range from 1 to 100 years for the following parameters

- Significant wave height (associated peak and mean period)
- Individual wave height (associated period)
- Crest height
- Current speed (possibly with tidal and surge part separated)
- Water level (possibly with tidal and surge part separated)

If the data material allows, then joint statistics for the parameters may be derived, such as the current speed associated to the design seastate.

If design of a foundation unit involves the use of a single design wave, this wave height should be the 100-year individual wave height. In many traditional designs, it has been assumed that the 100-year wave can be taken as the most like wave height occurring within the 100 year seastate. Within the oil and gas industry a more rigorous analysis is becoming the state-of-practice, in which the long term distribution of seastates is integrated with the short term distribution for individual waves to produce the long term distribution of extreme waves. The seastate distribution is typically derived from hindcast data, and the individual wave height distribution is often based on measurements.

Operational data
For planning of marine operations such as installation of the foundation and maintenance of the wind turbines the more frequent type of conditions are applied as basis for the statistical analyses. Typically continuous time series covering a number of years are applied as basis of the analysis. The reason for using more years is that the inter-annual variability can be quite significant, so data from a number of years are required to cover such variations.

The analyses focus on deriving more average statistics either for individual months, seasons or all year. All year statistics are used for fatigue analysis of the structures. The analysis will most often produce statistics for the occurrence (or exceedance) of certain prescribed conditions. In the simplest form the analyses neglect duration of conditions, and the statistics provide either exceedance probabilities for individual parameters (current speed, water level, wave height) or scatter diagrams (joint occurrence tables) for two-parameter conditions (current speed and direction, wave height and period, wave height and direction).

For operations where the duration of a certain hydrographic condition is important, so-called downtime or weather windows analyses can provide more detailed data. Most often a marine operation is limited by the seastate or maybe the wave period. Time series of the relevant parameter is therefore analysed to determine not only how much of the total time the limiting condition on average is exceeded but also for how long time (downtime) and vice versa (weather window). The output of such an analysis will tell the client the probability of having weather windows longer than say 24 hours in a given month or season, and thus assist in evaluating the risk for downtime. By analysing many years of data not only an average value but also a measure for the inter-annual variation in the average valued can be determined.

Weather windows statistics are excellent tools for planning purposes and for estimating risks and costs. However, it is the conditions prevailing during the actual operation that determines the actual downtime, not the statistics. The short term planning of marine operations can be substantially improved and made cost effective by applying forecast of weather as well as water parameters. Wave forecast has been applied for ocean traffic for many years, but the numerical models reviewed in this paper in relation to hindcast can also be applied for reliable forecast, even in the shallower water depths for wind farms. A successful application of such forecast is the installation of the Horns Rev wind farm and the on-going maintenance.

Finally, it shall be noted that state-of-practice hindcast and measurement programs and subsequent statistical analyses basically rely on the assumption that the future behaves like the past, at least in a statistical sense. Some caution is warranted concerning this assumption, due partly to a natural long term variation in the weather and partly to the emerging indicators of climate change.

Acknowledgements
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